

X-621-75-108
PREPRINT

NASA TM X- 70885

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(NASA-TM-X-70885) COULOMB COLLISIONS OF
RING CURRENT PARTICLES: INDIRECT SOURCE OF
HEAT FOR THE IONOSPHERE (NASA) 22 p HC
\$3.25 CSCL 04A

N75-22978

Unclas
20431

G3/46

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APRIL 1975



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COULOMB COLLISIONS OF RING CURRENT PARTICLES ¹

INDIRECT SOURCE OF HEAT FOR THE IONOSPHERE

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Abstract

The additional energy requirements of the topside ionosphere during a magnetic storm appear to be less than one quarter of the ring current energy. This energy is supplied largely by Coulomb collisions of ring current protons of energy less than about 20 keV with background thermal electrons which conduct the heat to the ionosphere. This paper rebuffs past criticisms of this mechanism for the supply of energy to the SAR-arc and neighboring regions of the ionosphere.

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COULOMB COLLISIONS OF RING CURRENT PARTICLES – INDIRECT SOURCE OF HEAT FOR THE IONOSPHERE

Earlier it was suggested that Coulomb collisions of ring current protons with background electrons in the magnetosphere may contribute significant amounts of heat for subsequent conduction via the background plasma into the ionosphere. Here the electron temperature may rise sufficiently to cause a SAR-arc observable from the ground above the background of emission of $\lambda 6300\text{\AA}$ which is due normally to recombination (Cole 1965). Cornwall et al (1971) claimed that Coulomb collisions were not an adequate source of energy from the ring current protons for this purpose. Rees and Roble (1975) noted a numerical error in Cole's (1965) calculation which further appeared to make the Coulomb collision mechanism an unlikely candidate. In fact Rees and Roble's (1974) estimate for the slowing down time of protons is not, as they claim, a factor of 25 different from that of Cole 1965 (his equation 13) but only a factor 10 (compare their Fig. 43). Moreover though he made this numerical error in estimating the slowing down time of protons Cole (1965) went on to use a more conservative value of this slowing down time which was only a factor of 3 different from what Rees and Roble (1975) estimate. The difference between the conclusions of Rees and Roble (1975) and Cole (1965) is that whereas Cole estimated the heat exchange all along the tube of force, Rees & Roble (1975) estimated it only for conditions near the equatorial plane. It is the purpose of this

note to treat the Coulomb collision decay problem in a more expanded way than has been done before and to restore it as a prime candidate for an energy source for heat conduction to the ionosphere from the ring current.

Earlier calculations, of which the author is aware, were somewhat biased to collisions near the equatorial plane of the magnetosphere whether in terms of the average density of thermal plasma in a tube of forces or by assumed particle pitch angle distribution (see e.g. Cole, 1965). These assumptions do not do justice to the Coulomb collisions mechanism for heat supply. We now know energy and pitch angle distributions much better (see Frank 1967, Smith et al 1974) and observations of plasma densities at 1000 km altitude (e.g. Norton and Findlay 1969) enable a better estimate of thermal plasma densities in tubes of force containing ring current particles.

Briefly, the result to be demonstrated in this paper is that because ring current particles exchange energy with background electrons more, the further they are from the equatorial plane, this increases the amount of heat made available by Coulomb collisions. The ring current particles below about 20 keV supply in this way enough additional energy for the midlatitude F-region and topside ionosphere during magnetic storms.

Additional Heat Requirements of the Midlatitude

Ionosphere During Storms

This heat is supplied largely by heat conduction from the magnetosphere (Cole 1965, Chandra et al. 1972, Rees and Roble 1975). It should be noted that

in 1965 Cole framed his discussion of this question around the stable auroral red arc (SAR-arc) because, at that time, the emission of $\lambda 6300\text{\AA}$ photons from atomic oxygen was the only available (indirect) source of information about the electron temperature (T_e). T_e was shown by Cole to be the energetically important parameter. However, it is the SAR-arc rather than T_e which appears to have captured interest. Now the consumption of energy in the ionosphere proceeds principally by collisions of electrons with ions and neutral particles and is therefore proportional locally to T_e or a low power of it whereas the emission of $\lambda 6300$ increases exponentially with T_e . So that small differences in T_e can make enormous differences to the amount of $\lambda 6300\text{\AA}$ photon emission that takes place. Therefore considerable consumption of energy of hot electrons in the ionosphere can take place without detection of significant emission of $\lambda 6300\text{\AA}$ intensity above the night background airglow which is due principally to recombination.

Since 1965 extensive measurements of electron temperature in the topside ionosphere have become available (Findlay and Brace, 1969) and one can infer the existence of a broad band of elevated electron temperatures and depressed electron densities at night extending from (and including) the SAR-arc up to the auroral zone (Findlay and Cole, 1970; Cole and Findlay, 1974). The SAR-arc feature is associated most often with a somewhat more elevated (T_e) and more depressed electron density (n_e) locally (i.e. a dimension about 500 km) within the broader range of 2000 km during a moderate magnetic storm. The consumption

of energy (per cm^2 column per sec) within a SAR-arc is greater than outside it and polewards of it within the broad band of elevated T_e and depressed n_e but there is still a significant flow of heat from the magnetosphere to the ionosphere in this broader region. The calculations reported by Roble et al. (1971) illustrate this point. This conclusion can also be substantiated by estimating the energy consumption by hot electrons in the F region through collisions with other species (Cole 1965). These estimates depend very much on the choice of ionospheric and thermospheric models (Chandra et al., 1972). A SAR-arc of intensity 1 kilorayleigh requires between 3 and $9 \times 10^{-2} \text{ ergs cm}^{-2} \text{ sec}^{-1}$ according to some recent calculations (Rees and Roble 1974). Such an arc would be associated with a storm which caused a 100γ depression of the geomagnetic field at the equator (Rees and Akasofu 1963).

Let us then conservatively assume (in the sense of this paper this means an overestimate) that $0.1 \text{ ergs cm}^{-2} \text{ sec}^{-1}$ are required for the SAR-arc at 45° latitude of width about 500 km and $3 \times 10^{-2} \text{ ergs cm}^{-2} \text{ sec}^{-1}$ in the belt of high electron temperatures between the SAR-arc and the auroral zone (Findlay and Cole 1970; Cole and Findlay 1974) (breadth about 1500 km). The total additional heat requirement for the ionosphere on account of these high electron temperatures is then $5.7 \times 10^{16} \text{ ergs sec}^{-1}$. This assumes equal heat flows during day and night, which assumption is not vital to the thesis of this paper, see discussion. Over the lifetime of the recovery phase of the magnetic storm, assumed here to be one day, this calls for an energy source of a total $5 \times 10^{21} \text{ ergs}$. As can be

seen from the next section this is only about one quarter of the energy of the ring current. Moreover, this would be an upper limit, and could be overestimated by a factor of 3. The calculations of Chandra et al (1972) show that for the same heat flux from the magnetosphere the integrated emission rate of $\lambda 6300\text{\AA}$ photons may vary by a factor 3 depending on the composition of the atmosphere assumed. These authors also pointed out that because of this sensitivity of atmospheric parameters, the criticism by Cornwall et al (1971) of the Coulomb source of energy proposed by Cole (1965) could not be sustained.

Energy in the ring current

Consider a moderate magnetic storm such as would cause at 100γ depression at the equator. The energy (E_n) available in the magnetosphere from the ring current during such a storm may be estimated by the Dessler-Parker-Sckopke relation

$$E_n = \frac{3}{2} E_m \frac{f \Delta B}{B_{eq}} \quad (1)$$

E_m = energy of geomagnetic field external to earth

f = fraction of disturbance ΔB due to ring current and not to induced current on the ground.

$B_{eq.}$ = strength of geomagnetic field at equator

ΔB = depression of geomagnetic field due to ring current and induced earth current.

The factor f was not included by Cole (1965) in his calculations. In the storm chosen we take $f = 2/3$ and it follows that $E_n \approx 2 \times 10^{22}$ ergs.

Coulomb Collisions of Ring Current Particles

with Background Plasma

We investigate here further the original hypothesis (Cole 1965) that Coulomb collisions of ring current particles with background plasma may be a major source of the energy for the ionosphere during magnetic storms. Until recently it was considered that only protons and electrons constituted the ring current. Now however there is the possibility that heavier ions including O^+ and He^+ may contribute significantly to this current (Shelley et al 1972). We have calculated the heating of thermal electrons by fluxes of energetic electrons protons O^+ and He^+ in a tube of force.

The slowing down time of an energetic charged particle is defined by (Spitzer 1962).

$$\langle \Delta w_{\parallel} \rangle t_s = -w \quad (1)$$

The rate of change of speed of a test particle

$$\langle \Delta w_{\parallel} \rangle = -A_D l_f^2 \left(1 + \frac{m}{m_f} \right) G(l_f w) \quad (2)$$

where $A_D = 8\pi e^4 n_f l \Lambda m^{-2}$

where w = speed of test particle

m = mass of test particle

m_f = atomic mass of particles constituting the field background

$\langle \Delta w_{\parallel} \rangle$ = rate of change of speed parallel to initial direction of test particle

n_f = number density of field particles

$l\Lambda$ = plasma parameter tabulated by Spitzer (p. 128)

$$l_f^2 = \frac{m}{2kT}$$

T = temperature of field particles

k = Boltzmann's constant

e = electronic charge

$G(1_f, w)$ = function derived from the error functions tabulated by Spitzer (p. 130).

Rather than estimate the slowing down time from equation (1) and then attempt a numerical estimation of the energy exchange between ring current particles and magnetospheric electrons all along a tube of magnetic flux, a new line of attack is presented which allows analytical calculation of this exchange in a fairly direct way knowing the fluxes of energetic particles and the electron density at one place in a flux tube. This now follows.

Thus if ϵ is the energy of the test particle then

$$\begin{aligned}\frac{d\epsilon}{dt} &= \epsilon \frac{2}{w} \cdot \frac{dw}{dt} \\ &= \epsilon \frac{2}{w} \langle \Delta w_{\parallel} \rangle\end{aligned}\tag{4}$$

Therefore

$$\frac{d\epsilon}{dt} = mw A_D^2 l_f^2 \left(1 + \frac{m}{m_f} \right) G(1_f w)\tag{5}$$

Consider now an isotropic flux, $F(w) dw$, of energetic particles of speed w .

Their number density is given by

$$dn = \frac{F(w) dw}{w}\tag{6}$$

It follows that the rate of exchange of energy by Coulomb collisions of this flux with the background (field) electrons is given by

$$Q = \int \frac{d\epsilon}{dt} dn = \int_0^{\infty} F(w) mA_D \left(1 + \frac{m}{m_f}\right) I_f^2 G(I_f w) dw \quad (7)$$

This formula is most useful when $I_f w \gg 1$. If $I_f w \gg 1$ then $I_f^2 G(I_f w) \rightarrow 1/2w^2$ (Spitzer 1962) and in this case

$$Q = \int_0^{\infty} \frac{F(w) mA_D \left(1 + \frac{m}{m_f}\right) dw}{2w^2} \quad (8)$$

For ions, equation 7 is appropriate in the application of present concern because we are interested only in the supply of heat with a time constant of order one day or less and this affects only the low energy ions. In the case of protons this applies to energies less than about 50 kev. For energetic electrons equation 8 is appropriate.

The rate at which energy is yielded up from low speed ($I_f w \lesssim 5$) particles to field electrons in a geomagnetic tube of force of unit area cross section at the ionosphere can be expressed in the following way

$$F(Q) = \int_T Q dV$$

where dV = an element of volume of the tube of force of unit area cross section at the ionosphere

$$= \frac{B_I}{B} ds$$

where ds = element of length along the tube.

B_I = magnetic field at the top of the ionosphere say at 1000 km altitude

B = magnetic field at points along the tube

The integral is performed over the whole tube (T) of force. It is assumed for present calculations that the density of field electrons in the tube of force is distributed (Cole 1963) according to the law $n \propto B$. This will be a good approximation for high temperatures. So it is assumed that

$$n_F = \frac{n_I B}{B_I}$$

It follows that for low speed particles

$$F(Q) = 8\pi \int_0^\infty \int_T e^4 F(w) m^{-1} \ln \Lambda \left(1 + \frac{m}{m_f}\right) l_f^2 G(l_f w) n_I dw ds \quad (9)$$

Similarly the heat flux into the background electron gas caused by high speed particles, integrated along a tube of force is given by

$$F(Q) = 16\pi \int_0^\infty \int_T e^4 F(w) m^{-1} \ln \Lambda \left(1 + \frac{m}{m_f}\right) w^{-2} n_I dw ds \quad (10)$$

Collisions of energetic particles with field electrons are sufficiently infrequent that to a first approximation Liouville's theorem may be applied to the energetic particles. With the assumption of an isotropic distribution in the equatorial plane (except for the atmospheric loss cone), we may separate the integrals on equation 9

$$F(Q) = 16\pi \int_0^\infty e^4 F(w) l_f^2 G(l_f w) dw \int_T \cos \alpha_L ds$$

where α_L = angle of atmospheric loss cone. The integral $\int_T \cos \alpha_L ds$ may be approximated by 0.5ℓ where ℓ is the length of the tube of force from the ionosphere to the equatorial plane. It follows that for low speed particles

$$F(Q) \approx 0.5 K n_I l \int_0^\infty F(w) l_f^2 G(l_f w) dw \quad (11)$$

and for high speed particles

$$F(Q) \approx 0.5 K n_I l \int_0^\infty 2F(w) w^{-2} dw \quad (12)$$

where l = length of tube of force from ionosphere to equatorial plane, which to a good approximation for a dipole is $(\pi/L-1)R_E$ where L = McIlwain parameter and R_E = radius of the earth.

$$K = 8\pi e^4 m^{-1} \left(1 + \frac{m}{m_f}\right) \ln \Lambda \quad (13)$$

where it has been assumed that $\ln \Lambda$ is approximately constant throughout a tube of force. Values of electron density and temperature in the magnetosphere make $\ln \Lambda \approx 20$ (Spitzer 1962) with a possible error of up to 20 per cent. For protons, He^+ , and O^+ $K \approx 2.94 \times 10^{-8}$ c.g.s. and for electrons $K \approx 5.87 \times 10^{-8}$ c.g.s. $F(Q)$ is the heat flux to the ionosphere.

Heating by Protons

The magnetic storm of February 24th, 1972 caused a depression of 70 to 80 γ and at this time proton fluxes with pitch angles near 90° in the magnetosphere near the equatorial plane at $L = 4.25$ were reported (Smith et al 1974). The energy range of the protons measured was from 1 kev to about 500 kev. It is assumed here that the proton fluxes are isotropic. In what follows an isotropic flux with the energy characteristics of the spectrum reported by Smith et al (1974)

is used to calculate the rate of heating of electrons in a tube of force at $L = 4.25$. Their spectrum has been multiplied by $100/75$ to make it appropriate for a 100γ storm which is being used as a model in this paper. A value of $n_I = 10^4 \text{ cm}^{-3}$ at 1000 km altitude has been assumed. Such densities have been measured over SAR arcs (Findlay et al., 1969). The estimate of $4.8 \times 10^{-2} \text{ ergs cm}^{-2} \text{ sec}^{-1}$ falls in the middle of the range of $3-9 \times 10^{-2} \text{ ergs cm}^{-2} \text{ sec}^{-1}$ suggested by the detailed calculations reported by Rees and Roble (1974) which are required for a 1 kR SAR-arc such as exists during a 100γ magnetic storm as measured by the field depression at the magnetic equator (Rees and Akasofu 1963).

Table 1

Energy spectrum of protons assumed in the magnetosphere at $L = 4.25$ during a magnetic storm of 100γ . Differential flux in units of $\text{cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1} \text{ kev}^{-1}$. Heat yield to electron gas in tube of force of unit cross section at ionosphere is $\Delta F(Q)$ in units of $\text{ergs cm}^{-2} \text{ sec}^{-1}$.

Energy (kev)	1	2	3	4	5	6	7	8	9	10
Diff flux	2.5^7	1.5^7	1.0^7	7.5^6	5.0^6	4.0^6	4.5^6	5.0^6	5.0^6	5.0^6
$\Delta F(Q)$	1.3^{-2}	8.3^{-3}	5.2^{-3}	3.5^{-3}	3.3^{-3}	1.5^{-3}	1.5^{-3}	1.5^{-3}	1.2^{-3}	1.2^{-3}
Energy	20	30	40	50	100					
Diff. flux	5.0^6	2.0^6	1.7^6	1.5^6	7.0^5					
$\Delta F(Q)$	5.9^{-3}	1.5^{-3}	7.9^{-4}	5.3^{-4}	8.0^{-4}					

Integrated heat flux $F(Q) = 4.8 \times 10^{-2} \text{ ergs cm}^{-2} \text{ sec}^{-1}$

The electron temperature is likely to be less than 10^4°K near 1000 km altitude but approaching 10^4°K or greater near the equatorial plane. Consideration of heat conduction in the electron gas suggests this. Even if the temperature is only 5000°K at 1000 km altitude this reduces the estimate of heat exchange by only about 20 per cent. The chief unknown is the electron density

at 1000 km altitude. The satellite data of Brace and Theis (1974) during one five day period show that in the vicinity of the plasmapause the electron temperature begins to rise (as latitude increases) from a value of 2500°K at a place inside the plasmapause where the density is 10^4 cm^{-3} at an altitude of about 3000 km. The electron temperature continues to rise as latitude increases and is 4000°K even though the altitude (of the satellite) is still 3000 km and the density dropped to $6 \times 10^3 \text{ cm}^{-3}$. By an $n \propto B$ law for density this would transpose into about $2.7 \times 10^4 \text{ cm}^{-3}$ at 1000 km altitude. At a higher latitude still where the electron temperature is 5000°K and the satellite altitude is 2800 km the density has dropped to $3 \times 10^3 \text{ cm}^{-3}$ or the equivalent of about $1.3 \times 10^4 \text{ cm}^{-3}$ at 1000 km altitude.

It is noted that $\Delta F(Q)$ in Table 1 increases as ϵ decreases to 1 kev and this suggests that there may be protons of energy less than 1 kev which contribute significantly to the heat flux.

In the observations of Smith et al (1974) and earlier measurements of Frank (1967) it is not clear to what extent He^+ , O^+ , N^+ or other heavier ions contributed to the flux measured. Observations of Shelley et al (1972) show that these heavier ions may, on occasion, account for up to 25% and more of the ring current energy. However, calculations of the energy loss by Coulomb collisions of energetic O^+ and He^+ suggest that this is a minor source of energy for magnetospheric electrons compared with protons.

Heating of background electrons by energetic electrons

Energetic electrons may contribute up to 25% of the ring current energy (Frank 1967) Table II shows the results of a calculation of the energetic electron losses by Coulomb collisions with background electrons. Use has been made of the spectrum of Barfield et al (1975) for the period 04-0500 UT on December 17, 1971 when D_{st} was about -40γ (Sugiura and Poros 1973). If we multiply the heat flux by 100/40 to scale it up to a 100γ storm we find only a contribution of $1.4 \times 10^{-3} \text{ ergs cm}^{-2} \text{ sec}^{-1}$ from electrons with energy greater than 1 kev. This is only 3 percent of the heat supplied by protons.

Table II

Energy (kev)	1	2	3	4	5	6	7	8	9	10
	2 ⁷	2 ⁷	2 ⁷	2.5 ⁷	2.7 ⁷	2.8 ⁷	2.8 ⁷	2.8 ⁹	1.9 ⁹	3 ⁷
ΔF(Q)	1.52 ⁻⁴	7.5 ⁻⁵	5.0 ⁻⁵	4.7 ⁻⁵	4.1 ⁻⁵	3.5 ⁻⁵	3.0 ⁻⁵	2.6 ⁻⁵	2.4 ⁻⁵	2.3 ⁻⁵
Energy (kev)	20	30	40	50	100					
Diff. flux	9 ⁶	10 ⁶	1.5 ⁵	5 ⁴	10 ⁴					
ΔF(Q)	3.4 ⁻⁵	0.5 ⁻⁵	—	—	—					
Integrated heat flux F(Q) = 5.4 ⁻⁴ ergs cm ⁻² sec ⁻¹										

Conclusions and Discussions

It is suggested from this analysis that the globally integrated additional heat requirements of the mid latitude ionosphere during a storm are only about one quarter or less of the ring current energy. This is somewhat less than suggested earlier Cole (1965) when crude calculations, hindered by lack of data at that time, could only indicate that the energy involved was of the order of the ring current energy. Sufficient energy is located in protons of energy less than about 20 kev.

It is clear that in the energy range greater than 1 kev protons yield up more energy than electrons by Coulomb collisions to the background plasma. In the case of protons this is a major energy loss mechanism for energies below about 30 kev. It is therefore, also a significant pitch angle scattering mechanism at these energies. The Coulomb collisions of the protons will tend to make the pitch angle distribution in the equatorial plane anisotropic because it would tend to cause the loss from the proton population of those with small pitch angles, for these encounter the greatest electron densities in their trajectories. Since it has been tacitly assumed in these calculations that the pitch angles of protons in the equatorial plane are isotropically distributed, or approximately so, a pitch angle scattering mechanism other than that provided by Coulomb collisions has also been tacitly assumed. Observations (Smith P.H., 1974 private communication) show that in the energy range of interest here ($<$ about 30 kev) that proton fluxes remain approximately isotropic during a storm. So apparently such a pitch angle scattering mechanism as is required here is in operation.

The data of Smith and Hoffman (1973), see their figure 3, show that the energy in the protons in the energy range 1-24 kev varies between $1/4$ and $1/2$ of the total energy in protons over the L value range from 3 to 5.5.

This analysis strongly suggests that at night a major portion of the energy requirements of the middle-latitude ionosphere during magnetic storms, including the energy required in the SAR-arc comes from protons of energy less than about 25 kev via Coulomb collision with the background electrons. This is contrary

to the conclusion of Rees and Roble (1974) who recently reviewed this subject. The physical reason for the difference in conclusion is that Rees and Roble (1974) biassed their discussion to the equatorial plane where densities of background electrons are low. However exchange of energy occurs all along a tube of force (Cole 1965) and particles spend most of their time near their mirror points (Hamlin et al 1961).

The greatest uncertainty in the present analysis is the electron density distribution along a tube of force in mid latitudes during a storm both inside and outside the plasmapause. The densities may be less than assumed in this paper. However it has been noted that protons of energy less than 1 kev may contribute significant amounts of heat. Unfortunately there are no measurements of proton spectra at our disposal in this energy range and it is hoped that future satellites will supply them. The present estimates of heating represent the best we can do with the available data at the present time.

Also Cornwall et al (1971) implied that Coulomb collisions were not a major transmitter of energy. However they required them as a "primer" to heat the electron gas so that ion cyclotron waves could be generated. If the mechanism of Cornwall et al (1971) needs to be involved it would be as an additional energy source for the electrons. The author is not aware of a quantitative estimate of the heating from this source. Particle-wave interactions of some kind would appear to be necessary to preserve approximate isotropy of low energy protons

in the equatorial plane, otherwise Coulomb collision would destroy this isotropy, by removing particles of low equatorial pitch angles.

It may be necessary to reiterate (see Cole 1965) that this mechanism is available at all times in the geomagnetic field even at supposedly quiet time. The geomagnetic field is rarely if ever, absolutely quiet and the only difference between quiet and storm times is a matter of degree and the spatial distribution of energetic and thermal plasma.

Acknowledgments

The author is indebted to the National Research Council of the National Academy of Sciences, U.S.A. for the award of a Senior post-doctoral research associateship and to NASA/GSFC for hospitality. The research reported here also forms part of a program of research supported at La Trobe University, Victoria, Australia by the Australian Research Grants Committee. The author also thanks Drs. P. H. Smith, R. A. Hoffman, T. A. Fritz, J. Barfield and S. DeForest and D. J. Williams for supplying information on energetic particle spectrums in advance of its publication.

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